ENGINEERING DEVELOPMENT OF A COAL-FIRED HIGH PERFORMANCE POWER GENERATNG SYSTEM

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ABSTRACT

United Technologies Research Center is heading up a team of seven research organizations to develop concepts and evaluate designs for a 300 Mw_e indirect fired combined cycle plant utilizing a 65% coal, 35% natural gas, fuel mix. The optimized design employs both radiative and convective air heaters to transfer the energy from coal combustion to the gas turbine working fluid. Because of present day materials limits, it is necessary to use a natural gas topping cycle to reach the appropriate turbine temperatures required for high efficiency.

Our design for the high temperature advanced furnace (HITAF) requires separating the air heater into a low temperature, dry ash convective section and a higher temperature, slagging ash radiant section. The major technical challenge of the program is in the development of the radiant air heater. Our approach is based on use of alloy materials protected by thick refractory coatings. The evolution of the design considerations will be presented.

INTRODUCTION

The Department of Energy (DoE) has recognized the need to make significant improvements to the overall thermal efficiency of coal-burning plants, while decreasing their environmental impact. Of all the proposed options for future coal-burning plants, the highest efficiencies are achieved by using Brayton cycles (gas turbines) rather than Rankine cycles (steam turbines). The DOE then initiated the research effort for a High Performance Power Generating System (HIPPS), which utilizes gas turbines but excludes all coal combustion products from the working fluid, thus avoiding the expense of hot gas cleanup and/or the corrosion of turbine blades by coal ash.

Because the gas turbine working fluid (air) is heated indirectly, the highest air temperature that can be reached by coal combustion is limited by heat exchanger materials and will fall short of the ideal turbine inlet temperature for highest efficiency. To achieve the desired turbine inlet temperature (approximately 2500°F) the program allows for up to 35% use of a premium fuel (e.g., natural gas or no. 2 heating oil) in a topping cycle. The design is still required to have a growth path to all coal as improvements in materials allow for a high temperature, corrosion/resistant heat exchanger. For the near term (<5 years) it is unlikely that there will be structural ceramics available that can withstand molten coal ash at temperature >2700°F for long times (10,000 hours). Therefore the present design must be based on materials available now or by the year 2000 and accept temporary limitations on the maximum air temperature from coal combustion.

The program devised by DOE has three phases: Phase I - Concept Definition and Preliminary R&D, begun in 1992; Phase II - Engineering Development and Testing, which started in 1995; and, Phase III - Prototype High Performance Power Plant, planned to start in 2000.

The HIPPS designs are required to meet or exceed the goals listed in Table 1.

Table 1.

	Phase I	**Phase II**	**NSPS**
Pollutant Emissions			
NO_x (lbs NO_2/MBTU fuel)	0.15	0.06	0.6
SO_x (lbs SO_2/MBTU fuel)	0.15	0.06	0.6
Particulates (lbs/MBTU fuel)	0.0075	0.003	0.03
Thermal efficiency (HHV) ≥ 47%			
All solid wastes begin			
Coal must ≥ 65% total fuel (and path to 95% coal)			
COE ≤≤ 90% present cost for NSPS plant			

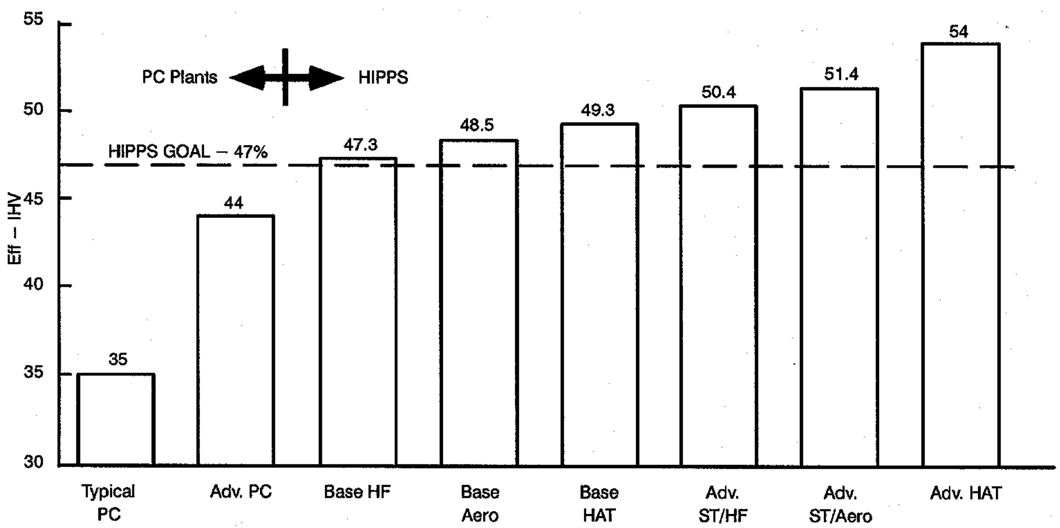


Fig. 1. Efficiency of Coal-Fired Systems

APPROACH

The UTRC team has developed a design based on a thermodynamic optimization study of a combined cycle 300 MW plant, using an advanced aeroderivative gas turbine and a commercially available steam turbine. The working fluid is heated, using both radiative and convective air heaters. The convective air heater is constructed of ferritic alloy and a radiative air heater that is constructed from Ni-based superalloy protected by a ceramic refractory coating.

The three major elements of the system are the High Temperature Air Furnace (HITAF), the gas turbine, and the steam turbine. The HITAF supplies 55% of the temperature rise required by the gas turbines, bringing the compressor discharge air to 1700°F. The air then goes to a duct burner, where natural gas combustion boosts the temperature to that required by the turbine. The turbine exhaust stream, along with that from the HITAF, furnishes waste heat to a heat recovery steam generator (HRSG) and steam turbine. The overall efficiency of this system exceeds 47%, significantly better than typical PC plants.

The baseline plant design is a non site-specific, greenfield power generation plant and includes all facilities required for power production. Consistent with the June, 1993 EPRI TAGTM, the HIPPS plant boundaries for design and cost estimates include all the major operating systems such as the HITAF unit, heat recovery steam generators, gas turbine, environmental control equipment, auxiliary equipment and all support facilities needed to operate the plant.

The baseline cycle is only one case of the family of cycles we have been studying. Our goal is to find the optimum cycle to exploit the HIPPS technology. A chart showing the potential performance of several advanced HIPPS cycles based on the HITAF is shown in Figure1. The original baseline system used a heavy frame gas turbine and a 2400 psi/1000°F/1000°F bottoming cycle and gave an overall efficiency of 47.3%.

The Phase II baseline cycle is an advanced aeroderivative gas turbine/combined cycle using the same steam system. In addition, several advanced technology power plants are also under evaluation:

- aero-derivative Humid Air Turbine (HAT) cycle,
- heavy frame turbine/advanced steam combined cycle,
- advanced aero-derivative/advanced steam combined cycle, and
- advanced aero-derivative Humid Air Turbine (HAT) cycle.

Using the same engine technology level, a preliminary evaluation of an Humid Air Turbine (HAT) cycle indicated that efficiencies of over 49% could be realized. This cycle has not been fully optimized at this time. Additional configuration changes might add as much as two efficiency points (efficiencies of 50-51%).

The detailed analysis of the heavy frame advanced steam system has not been carried out. Based on the preliminary analysis of the aero-derivative/advanced steam cycle, however, it is valid to assume that efficiencies of over 50% might be attained.

The advanced steam aero-derivative cycle has been the subject of a preliminary analysis, but has not been optimized. The gas turbine has the same technology as used in the foregoing aero-derivative turbines, but uses steam injection for power and efficiency increases. The steam cycle advances are based on efforts being pioneered by Innovative Steam Technologies. The system has a 6200 psi/1300°F high pressure steam turbine exhausting directly into a 2400 psi system similar to those used in the preceding configurations. This system is currently being analyzed; preliminary estimates of efficiency are in the 51-52% range.

The advanced HAT cycle system is based on an aero-derivative turbine using technology identified in previous DOE- and EPRI-sponsored studies. The combustor exit temperature is of the order of 2900°F. Preliminary analysis has indicated that efficiencies of better than 54% could be anticipated.

It should be noted that all of the cycles using aero-derivative turbines have not been pushed to the limit of possible turbine technology. Rather, they reflect projected technologies for time of appearance, i.e., late 1990's, early 2000's. For cycles with moisture addition, either with steam injection or with saturation (HAT), higher turbine temperatures can be postulated. For example, a previous DOE study described a HAT cycle based on turbine temperatures of over 3100°F, using advanced cooling techniques currently being developed for military aircraft engines. A cycle efficiency of over 63% (LHV methane) was estimated. Using this turbine technology with other configuration changes, such as a reheater, might result in HITAF-based systems with efficiencies over 56% HHV and outputs approaching 400 MW per unit. This turbine technology could also be used with advanced steam combined cycles and might reach 54% HHV.

HITAF Air Heater

Since the high temperature products of coal combustion will provide the heat source for the proposed HITAF concept, the air heaters must be capable of operation under unusually severe conditions. While conventional coal-fired steam power plants experience similar operating conditions, the air temperature required from the HITAF is of the order of 1700°F or more compared to only about 1000°F for steam, and air is a poor heat transport fluid compared to steam. The process of transferring heat from coal combustion products at about 3000°F to high pressure air will require special structural design of the air heaters in order to avoid excessive mechanical and thermal stresses. Moreover, the mineral content of most coals at typical combustion temperatures produces ash particles in the combustion gas stream, resulting in potential for heat transfer performance degradation, as well as corrosion and erosion of air heater surfaces. Although erosion of air heater surfaces by impinging ash particles is not expected to be a problem because gas and particle velocities will not be excessive, special provisions will be made to minimize heat transfer degradation and to prevent corrosion.

In order to produce the high air temperature required for acceptable gas turbine efficiency, the coal combustion temperature will have to be sufficiently high to produce molten slag which can potentially foul and corrode heat transfer surfaces. Since the entire air heater cannot be maintained hot enough to produce continuous slag flow from all heat transfer surfaces, the transition from wet slag to dry ash will be controlled by separation into two different types of air heaters which will be designed to deal exclusively with slag or ash. The radiant air heater (RAH) will operate at the higher temperature levels required, while the convective air heater (CAH) will function at the lower temperature regime. The air heaters will be arranged for counter flow of the gas turbine air and the coal combustion gas so as to achieve the highest possible temperature differential. A slag screen will be located between the two air heaters to establish the wet-dry interface (wet slag to dry ash) and to remove most of the ash from the hot gas stream before it can enter the convective air heater. To prevent excessive sintering of ash deposits on heater surfaces and to provide a suitable temperature zone for selective non-catalytic reduction of NO_X, the combustion gas temperature will be reduced to about 1800°F by introducing flue gas recirculation immediately upstream of the convective air heater. This arrangement of the air heaters and the slag screen are shown schematically in Fig. 2 along with expected operating temperature levels. The rationale for this arrangement of the air heaters, their respective operating conditions, and unique design features are discussed below in relationship to operating temperature levels and slag and ash environments.

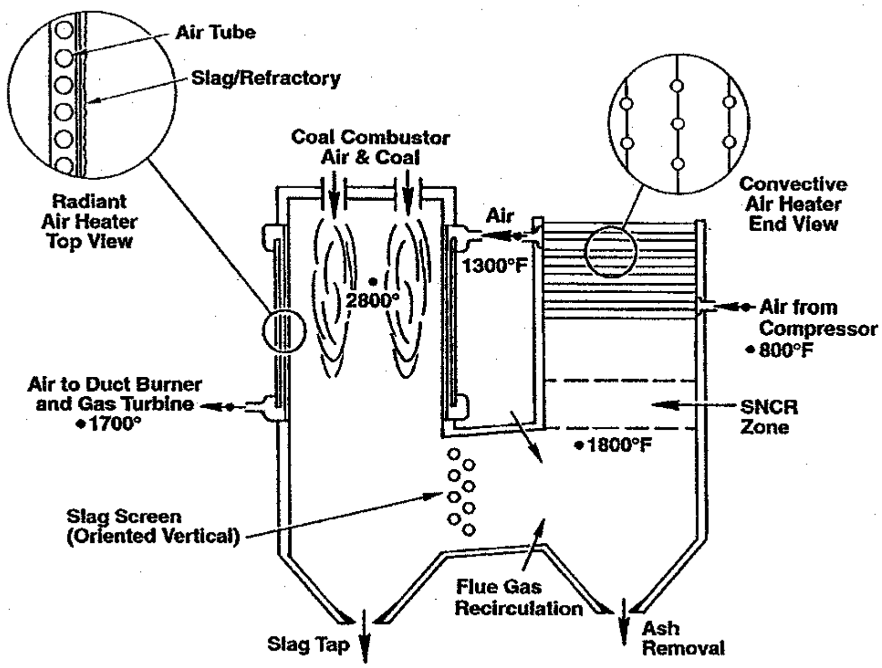


Fig. 2. UTRC Arrangement of HITAF Components

Radiant and Convective Air Heater Design Concepts

Conceptual design for the radiant air heater is shown in Fig. 3. The radiant air heater will consist of an array of tubes contained in a protected panel that will be uniformly heated by radiation and will line the inside walls of the coal combustion furnace. The gas turbine air will be distributed to the many small passages within these panels by an arrangement of headers, manifolds, and ducts which will be staged to avoid excessive thermal stresses. A ceramic refractory coating or tiles will be applied to the fire sides of the hollow panels to prevent slag-induced corrosion. Although the radiant air heater is adaptable for either parallel or counter flow of the hot and cold gas streams, parallel flow will enhance draining of liquid slag from the radiant heater surface by producing the highest surface temperature at the lowest point of the heater. Structural support for the entire radiant air heater will be provided by a massive structural shelf at the bottom of the furnace, probably consisting of furnace brick masonry. The high temperature coal combustion products at 2800°F or higher will heat the panels by radiant transfer and, as the gas turbine air flows through the panels, the air will be heated by forced convection from about 1300°F to 1700°F or higher, depending on heater material and availability of supplemental heating by direct combustion of natural gas or oil. If the air temperature out of the radiant heater is limited to 1700°F, nickel-based metal alloys which have been developed for the aircraft gas turbine industry can be used to withstand an expected maximum heater temperature up to 1900°F.

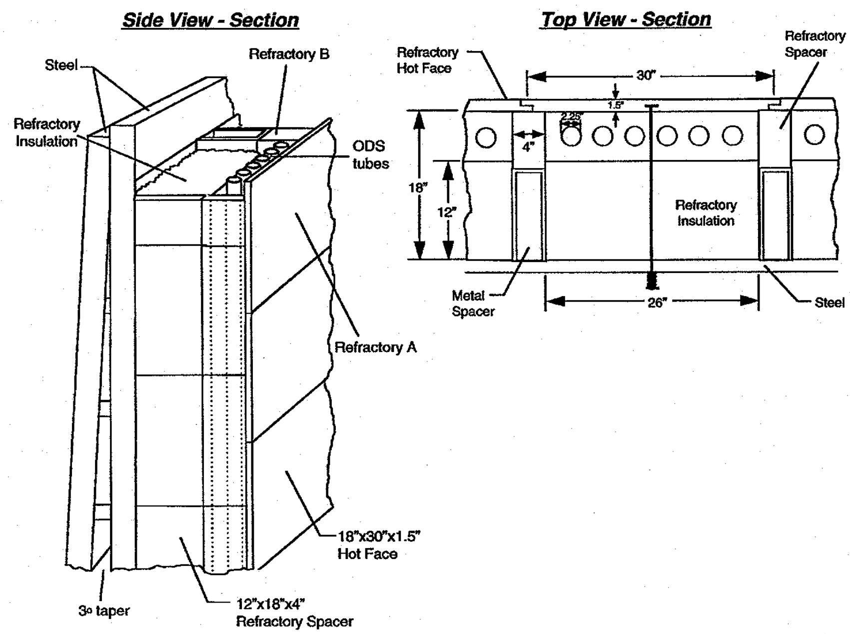


Fig. 3. Hot Sections of Radiant Air Heater

Air Heater Materials

Materials are the key enabling technology for successful operation and commercialization of the HIPPS system. The use of high temperature heat exchangers in a coal combustion environment, coupled with the cost constraints, make proper materials selection a considerable challenge. Nonetheless, utilization of state of the art materials and joining methods, as well as advanced oxidation and corrosion resistant coatings, can yield reasonable compromises.

The RAH must tolerate running coal slag on it's inner surface, while providing protection and reasonable heat transfer to the working fluid (air) contained near the outer walls of the coal combustor. Phase I efforts have indicated several potential approaches for this component: 1) use of metal tubing with protective coating(s) and refractory ceramic lining(s), 2) use of structural ceramics such as silicon carbide or silicon carbide /alumina particulate composites, with a protective refractory ceramic lining, and 3) use of fusion cast ceramics such as those used for glass furnace tank linings.

The use of a metallic based RAH, particularly under moderated temperatures and environments afforded by the 65% coal combustion case offers several advantages: 1) ease of fabrication, (i.e. conventional processes can be used to shape and weld components); 2) existence of a significant supplier base; and 3) high strength under moderate (65% coal) system conditions. These alloys offer superior performance compared to the steels, currently utilized in similar applications such as water wall slagging coal combustors. However, it is clear that, for the radiant air heater section, a system of refractory ceramic linings (with or without supplemental thin coatings on the base alloy) will be required to protect the alloy from the slagging coal ash environment. A diagram of an RAH wall cross-section is shown in Fig. 3.

The use of structural ceramics and/or fusion cast refractories have some disadvantages. Joining and sealing technologies are not well developed. For structural ceramics, while a supplier base exists for producing relatively large tubes, production costs remain high. Moreover, fusion cast ceramics are not normally produced as hollow shapes. Nonetheless, the allowable use temperatures of these ceramic materials make them the primary alternatives for use in the "all coal" combustion case when the working fluid is heated to 2500°F or higher.

The metal based approach to the RAH clearly offers a high probability of success for fabricating and operating a prototype HIPPS system. All of the various material elements (metals, coatings, and ceramics) that make up this approach to the RAH wall will require careful testing to determine survivability in coal combustion environments. In addition to selecting and testing of metals, coatings, and refractory ceramic liners, consideration must be given to both on-line and off-line repair of the materials during use. Techniques for bonding, joining and attaching both the dissimilar materials of construction and individual wall subsections will require development and validation.

Radiation Modeling

A radiation program has been created to determine and optimize the heat transfer from the outer refractory wall to the air in the tubes. The total heat transfer per unit RAH surface area is represented as a function of hot surface temperature, air temperature, air-side convective coefficients and geometry. From this, an effective convective coefficient is expressed as a function of the hot refractory surface temperature and the air temperature for a given geometry and material properties, and air-side convection coefficient.

The tube is broken into a total of 12 elements of equal circumference. A symmetry plane exists vertically through each tube, and therefore only 7 independent elements need to be defined. Each tube element has its own temperature and emittance.

The re-radiating plane (insulating wall behind tubes) is also broken into elements. There are 4 equally sized elements under each tube, and 3 equally sized elements in the space between the tubes. Again due to symmetry, only 4 independent elements need to be defined. Each refractory element may have its own temperature and emittance. The hot surface is treated as a single element.

For each element, radiation shape factors are determined as functions of the geometry parameters, defined from the element's center. Since there are many iterations, an iterative method of solution was developed where the following sub-problems are solved separately;

- The re-radiating plane temperature distribution is found assuming that the tube temperature distribution is known and fixed.
- A single tube temperature distribution is found assuming that the other tubes and the re-radiating plane is known and fixed.

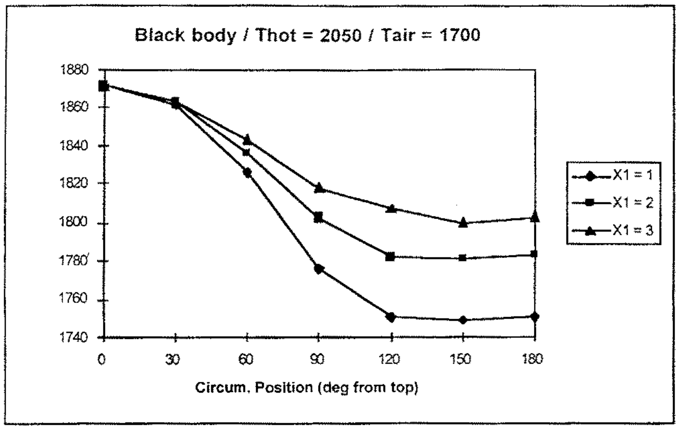
Within each sub-problem, the temperature of each element is relaxed until the prescribed boundary heat flux is obtained. Iteration is required at each sub-problem level, and between the two sub-problems. The temperature distribution of the neighboring tubes is taken as the previous iteration solution.

The analytical model indicates that:

- Increasing the tube spacing (X1) increases the temperature of the re-radiating surface, which increases the transfer to the "cold" side of the tubes. As the tube spacing increases, the amount of heat transfer per tube increases, but the number of tubes per RAH area decreases. Overall, it was found that the heat transfer per unit area decreases with increasing space between the tubes, but the tube temperature profile became more uniform, and therefore resulted in less thermal stress and deflection.
- With increasing RAH size and decreasing normal heat flux, the refractory can provide more insulation and therefore can be thicker.

- Increasing the tube to wall spacings (Y1, Y2) increases the uniformity of the refractory temperature profile. It was found that a spacing of approximately 1 tube diameter is sufficient.
- The emittance of both the hot surface and the tubes determines (together with the geometry) the effective gap resistance. The emittance of the re-radiating surface (assuming negligible heat loss) does not.

Figure 4 shows the temperature profiles of the tube (black body) for various tube spacings.



Temperature Distribution Around Single Alloy Tube

Fig. 4. Temperature Distribution Around Single Alloy Tube

In the RAH design, various material constraints must be considered. Since the “tubes-in-a-box” design relieves the stress problem in the alloy tubes, the tube properties no longer constrain the problem. The current design is being constrained by the minimum allowable refractory thickness. Because of this it is not expedient to vary the emissivity of the tubes, since it leads to higher overall gap resistance.

Testing in the Pilot-Scale Slagging Furnace.

The pilot-scale slagging furnace design is intended to be as fuel-flexible as possible, with furnace exit temperatures of at least 2700°F in order to maintain desired slag flow. It will have a nominal firing rate of 2.5 million Btu/hr and a range of 2.0 to 3.0 million Btu/hr using a single burner. The design is based on a bituminous coal (Illinois No. 6, 11,100 Btu/lb) and a nominal furnace residence time of 3.5 seconds. Resulting flue gas flow rates will range from roughly 425 to 640 scfm, with a nominal value of 530 scfm based on 20% excess air. Firing a subbituminous coal or lignite will increase the flue gas volume, decreasing residence time to roughly 3 seconds. However, the high volatility of the low-rank fuels will result in a high combustion efficiency (>99%). The furnace will be oriented vertically (downfired) and base the burner design on a swirl burner currently used on two EERC pilot-scale pulverized coal (pc)-fired units that are fired at 600,000 Btu/hr. Slagging furnace dimensions will be 48-in. inside diameter (ID) by roughly 16 ft in length. Combustion air preheat capabilities will range from 300° to 900°F.

The primary burner will be natural gas- and coal-capable, with coal particle size assumed to be a standard utility grind, 70% -200 mesh. Burner development and testing are not objectives within this activity. However, some burner turndown is desirable and has been factored into the burner design. Flame stability will be assessed by observation of the flame and its relation to the burner quarl as a function of secondary air swirl and operating conditions at full load and under turndown conditions. The basic burner design, an International Flame Research Foundation (IFRF)-type adjustable secondary air swirl generator. An IFRF-type adjustable secondary air swirl generator uses primary and secondary air at approximately 15% and 85% of the total air, respectively, to adjust swirl between 0 and a maximum of 1.9.

Secondary air swirl is used to stabilize the flame. In the absence of swirl, loss of flame may result, increasing the risk of dust explosion. As swirl is applied to the combustion air, coal particles are entrained in the internal recirculation zone, increasing the heating rate of the particles, leading to increased release of volatiles and char combustion. The flame becomes more compact and intense as swirl is increased to an optimum level, which is characterized in existing EERC pilot-scale test facilities as the point at which the flame makes contact with the burner quarl. Increasing swirl beyond this level can pull the flame into the burner region, unnecessarily exposing metal burner components to the intense heat of the flame and possible combustion in the coal pipe.

Increasing swirl to provide flame stability and increased carbon conversion can also affect the formation of NOx. The high flame temperatures and increased coal-air mixing associated with increased swirl create an ideal situation under which NOx may form. In full-scale burners with adjustable vanes, swirl is often increased to reach the optimum condition and then decreased slightly to reduce the production of NOx. Although NOx emissions are of interest, their control is not a key objective for the pilot-scale slagging furnace. Therefore, burner operational settings will be based on achieving desired furnace exit temperatures and slag conditions in the furnace.

Flame stability under turndown conditions will be characterized by firing the test fuel at reduced load (typically 66% to 85% of the full load rate), maintaining the same primary air flow and adjusting the secondary air flow to meet excess air requirements. At this time, it is planned to simply scale up the existing burner design based on increased combustion air volumetric flow rates. If desired, the final burner design may be reviewed with the project team organizations interested in those details.

Observation ports will be located in the furnace to permit visual observation of the primary burner flame, auxiliary burner flame, RAH panels, slage screen, and slag tap. In order to adequately characterize the furnace during shakedown and since RAH test panels will not necessarily be available for all furnace operating periods, the first set of doors built for the RAH panel locations will have ports to permit the insertion of temperature and heat flux measurement probes.

An auxiliary gas burner (500,000 Btu/hr) will be located in the area of the furnace exit in order to ensure desired slag flow from the furnace and the slag screen. This auxiliary burner will compensate for heat losses through the furnace walls, site ports, and RAH test panels. The use of the auxiliary gas burner will be beneficial during start-up to reduce heatup time and to prevent the freezing of slag on the slag screen when initially switching to coal firing. The auxiliary gas burner will be fired at stoichiometric conditions to avoid high excess air levels in the system. Also, the auxiliary gas burner will be fired at relatively low rates (<200,000 Btu/hr) once the furnace reaches thermal equilibrium. The overall pilot-slag furnace is illustrated in Fig. 5.

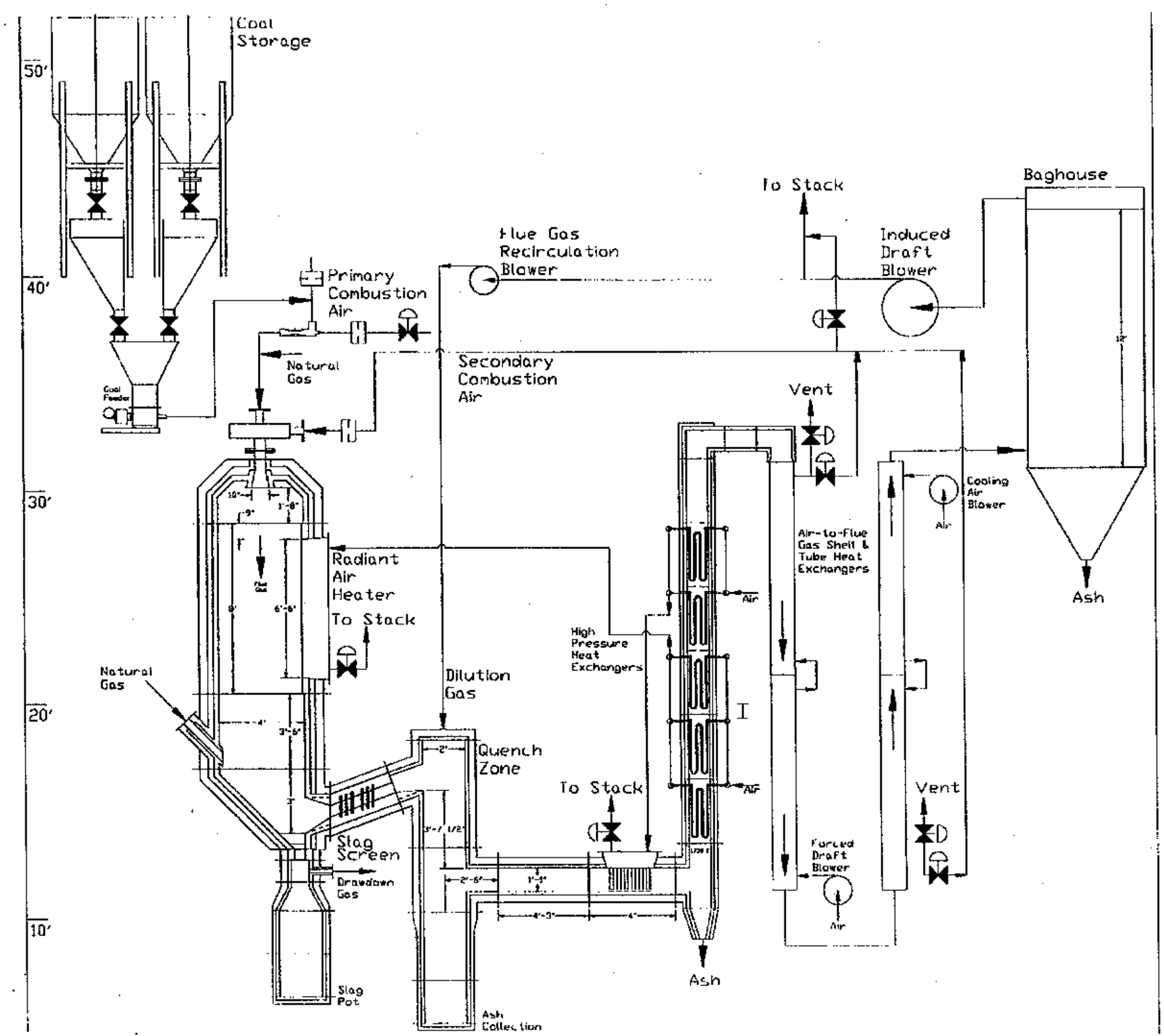


Fig. 5. Combustion 2000 Furnace and Support Systems